THE CASE FOR INHERENT STABILITY OF HELICOPTERS

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INTRODUCTION

Helicopters have been built in many configurations. They have exhibited a multitude of stability problems in the past, many of which are still present to some degree in the present generation of helicopters. We do not have enough knowledge to design into the aircraft all the flying qualities we want or need for any specific mission. Therefore, it seems certain that stability and/or control augmentation of some sort will be used for advanced, higher performance helicopters. However, protection against failures of augmentation systems in the form of minimum inherent stability characteristics of the basic aircraft is required. It is considered within the state of the art nowadays to design for an adequate level of inherent stability in forward flight for the common configurations.

In this paper I will discuss the nature of the stability characteristics of concern, the trade-offs in applying augmentation to achieve the desired flying qualities, and minimum requirements for inherent stability should the augmentation fail.

NATURE AND SIGNIFICANCE OF HELICOPTER INHERENT STABILITY CHARACTERISTICS

Static stability, the presence of restoring moments such as the weathervane experiences when pointing into the wind, can exist only with respect to a relative wind. In hovering flight neither a helicopter or any other VTOL will experience aerodynamic righting, or restoring moments from an upset or a gust with controls fixed until motion through the air results. The only inherent stabilizing term that is present in hover is the damping or resistance to an angular velocity generated by the rotor system in the case of the helicopter. This damping only slows the rate at which the helicopter is upset when disturbed.

In forward flight static moments are generated which, combined with the damping, may either tend to restore the aircraft to initial conditions, or tend to cause it to deviate further.

Characteristics of unstable helicopters that are of most concern occur at high speeds and are a result of static instabilities similar to those of a weathervane when its tail is to the wind. Sources for static longitudinal instability in a helicopter are: the fuselage; unstable flapping of hinged rotors with respect to an angle-of-attack change which is accentuated when blade stalling is encountered; and, in the case of tandem types, unstable downwash effects. The main source for static directional instability which has been a problem with some types, including the tandem, has been the fuselage. Effective dihedral or the rolling moment generated by sideslip has generally been stable, but with some configurations it has been unstable. The significance of each of the instabilities will be discussed in turn.

Instability with Angle of Attack

Instability with angle of attack is the most violent and dangerous form of instability exhibited by helicopters. It is similar to the instability exhibited by an airplane when its center of gravity lies aft of the maneuver point, and results in a divergence in pitching velocity, normal acceleration, and attitude with controls fixed. This type of instability is nonexistent in hovering and increases in severity with the tip-speed ratio and the loading of the rotor or rotors. At high speed it may result in complete and sudden loss of control from which structural failure or dangerous flight attitudes can result. Figures 1 and 2 are time histories from exploratory flight tests of a very early helicopter (ref. 1) which illustrate the point. This helicopter did not have tail surfaces, had no flapping hinge offset, and used a fairly low rotor rpm. In figure 1 the aircraft exhibits an expanding oscillation with controls fixed at 40 mph, the speed for minimum power. The oscillation is a combination of positive stability with respect to a speed change (to be discussed later) and an instability with an angle-of-attack change. At 65 mph in figure 2 the instability with angle of attack has increased to the extent that, insofar as the pilot is concerned, the aircraft exhibits a pure divergence with controls fixed. The pilot in figure 2 first attempts recovery from a nose-down divergence, but as soon as recovery begins the aircraft begins a divergence in the nose-up direction and the pilot is forced to move the stick in a continuous manner to the forward stop where it is held for about 2 to 3 seconds before the acceleration peaks at 1.75g. Actually the pilot had to reduce collective pitch and roll the aircraft into a wing-over to make a safe recovery because of the severe nose-up attitude reached.

Figure 3 is an analytical curve for a flapping rotor of current design showing the incremental control displacement to trim in a maneuver of 1.5g as a function of speed. The curve is estimated from the latest available charts of rotor characteristics (ref. 2). The dashed portion of the curve represents the onset of blade stalling. The characteristics can be considered to represent a helicopter in which the fuselage has been stabilized sufficiently to make its pitching-moment variation with angle of attack zero. As can be seen, the stick displacement to trim is unstable in direction, indicating strong pitch-up or divergent tendencies, and it would reach the forward stop at 1.5g at about 170 knots. Should 1.5g be exceeded at 170 knots, or the speed exceed 170 knots at 1.5g the aircraft would pitch up further out of control. In practice this instability could not be permitted to reach this degree of severity.

In the case of the tandem-rotor helicopter configuration the rotor flapping instability with angle of attack is also the largest source of instability at high speeds. The tandem has an advantage over the single-rotor helicopter in that it has a high longitudinal control moment available from differential collective pitch change of the two rotors. However, with controls fixed the rate of divergence can be high if sufficient stabilization or augmentation is not provided. Figure 4 shows the divergence of a proposed tandem helicopter configuration (ref. 3) without stability augmentation. The characteristics were derived analytically from fuselage wind-tunnel studies and the same rotor charts as were used for figure 3. The average blade lift coefficient was kept the same as for the single rotor of figure 3. In this figure the helicopter was disturbed from trimmed steady flight by an 0.1-second pulse of 10 percent of its control power. Note that a limit load factor of $2\frac{1}{2}$g would be reached with controls fixed in about $3\frac{1}{2}$ seconds at an attitude of about 25° nose up. Since the divergence begins in a rather slow manner, the pilot may not always become aware of the divergence until perhaps 2 seconds have elapsed, so actually he has a shorter time to take recovery action than indicated. There is no doubt that a pilot can fly such a divergent aircraft for short periods even on instruments, provided he has no distractions. However, a pilot has many distractions such as the operation of various aircraft systems, accomplishing flight planning, performing navigational problems, communicating with and following air traffic control instructions, and handling emergencies. A divergent aircraft during such periods is a difficult, distracting, and dangerous aircraft.

In a recent study of jet airplane upsets from which loss of control was experienced during instrument flight it has been suggested by some analysts (ref. 4) that the pilots were confused by clues resulting from sustained normal accelerations combined with their own corrective action such as might occur in updrafts. For instance, the pilot puts in nose-down control as the updraft accelerates the aircraft upward, but the airplane accelerates longitudinally because of the reduced drag at lower angles of attack and load factor. This swings the gravity vector apparent to the pilot rearward, giving the pilot the impression that he is nosing up further into a loop. He therefore struggles to push the nose down further, although the nose may actually be too far down already. Buffeting and shaking of the airframe at about 4 cps at the same time causes the pilot's eyes to dance and he is not able to ascertain attitudes clearly from the flight instruments. Thus a dive and severe overspeed result.

The divergent tendencies of the subject helicopter, particularly considering flight in turbulent air, may exaggerate the tendencies toward such confusion and upsets, particularly since all the ingredients including vibration at 4 to 6 cps, are apt to be present.

Instability With Speed

With flapping rotor systems the flapping tends to increase with an increase in forward speed, and vice versa, thus tending to return the aircraft to the original trim speed. This flapping is illustrated as a stick position for trim in figure 5. However, fuselage moments, horizontal tail loads, blade pitching moments which twist the blades, and downwash effects for the tandem-rotor configuration sometimes result in an instability with speed. This is usually mild and produces fairly slow divergence compared with that due to angle-of-attack instability. However, it may easily couple with angle-of-attack instability to produce more rapid divergence. If the aircraft is stable with respect to angle of attack, speed instability may be of no consequence. Speed instability can be dangerous, however, if the trim position of the control approaches one stop or the other. This has occurred in some early tandem-rotor types. Figure 6 shows stick position to trim with speed at a constant collective pitch and power control setting for a typical tandem-rotor helicopter (ref. 5). The slope of the curve indicates instability with speed. However, the rate of divergence from trim speed with controls fixed, although moderate in this case, cannot readily be appreciated from a curve such as this because the control power has to be taken into account.

Static Directional (Weathercock) Instability

Several types of helicopters, notably the tandem-rotor type, have exhibited directional instability through large ranges of sideslip angle. Figure 7 shows the rudder pedal position to trim versus sideslip for a typical tandem-rotor helicopter in cruise (ref. 5). No stable trim points are indicated for this condition in either direction. Again, the control power must be taken into account in judging the severity of the instability in terms of divergence. Changes in power, angle of attack, and speed change the nature of the directional-stability characteristics. Since yaw control in tandem-rotor types and others without tail rotors has tended to be low, considerable effort has to be expended to keep the aircraft flying at zero sideslip. The pilots have tended to let the aircraft trim at stable trim points, when they exist at some sideslip angle other than zero. In such cases considerable error could result during navigational flights if sideslip angle is not known nor properly accounted for. Also, drag would certainly go up at sideslip angles other than zero so that speed, range, and endurance would suffer. Lateral maneuvers tend to result in severe adverse yawing and sideslip when low or negative directional stability exists. This results in delayed turns, a reduction or reversal in rolling velocity, or difficulty in coordinating turns by use of the directional control. Figure 8 from data of reference 6 shows some of these characteristics from flight tests of a tandem helicopter which had low but positive directional stability. During this pedals-fixed roll the heading did not begin to change in the desired direction for 3 seconds, and the rolling velocity reversed. The inability to keep sideslip small also requires lateral controlling and retrimming due to dihedral effect to prevent continual turning flight. As speeds increase, the yaw control moments available in the tandem tend to remain constant, whereas the yawing moments of the fuselage tend to increase with dynamic pressure. Large excursions in sideslip which are apt to occur at high speed, therefore, may well lead to excessive structural loads and rolling moments. At any rate the sideslip excursions would result in a very uncomfortable ride for the occupants.

Effective Dihedral

Effective dihedral is another form of static stability which defines the direction of roll with sideslip. It is usually positive, or in a direction to bank the aircraft away from the sideslip and to reduce it. It can be too great for good flying qualities in some cases. However, for some configurations the effective dihedral has been negative, although generally to a mild degree. With negative dihedral the aircraft tends to roll into the sideslip so as to increase it. If static directional stability is positive, negative effective dihedral may never be noticed. However, if an appreciable degree of negative dihedral is present in combination with directional instability dangerous characteristics may result. The motion of the aircraft with controls fixed would then be similar to an automobile in an increasing skid from which it rolls over to the outside. Another case where negative dihedral could be troublesome is where a heading-hold system is provided with no stability augmentation about the roll axis. Should the aircraft bank due to some upset, sideslip and bank slowly diverge as long as the heading is being held fixed. The rate of such a divergence would probably be low.

USE AND LIMITATIONS OF STABILITY AUGMENTATION SYSTEMS

Providing inherent stability of the basic airframe to correct the problems discussed will ensure relative safety but may not necessarily provide the desired flying qualities in a given helicopter. This is because the proper magnitudes of the static stabilities and angular velocity dampings about the several axes to be used in combination in a particular configuration are either not known or cannot be obtained readily. The solution to tailoring the flying qualities as desired lies in the use of stability and control augmentation. It is assumed, therefore, that all high-speed helicopters and helicopters intended for instrument flight will have some form of stability and/or control augmentation for normal operation. The augmentation may use aerodynamic, mechanical, pneumatic, hydraulic, electronic or other means for sensing and making inputs to the basic control system.

The philosophy preferred with regard to augmentation, however, is that it be used to improve the efficiency and capability of performing the basic mission of the aircraft, and not for overcoming serious deficiencies in stability and control of the basic airframe. This philosophy implies that if a single failure of the augmentation occurs the pilot can still perform the basic mission with a margin of safety, and if all augmentation is lost the aircraft can be flown to a base and landed safely with some acceptable deterioration in its mission capability. This philosophy also implies that the basic airframe should have inherently good stability characteristics such that single-channel systems of limited authority would be adequate and safe except, perhaps, for specialized portions of a mission such as the instrument approach in very low visibility.

Reliability

The key factor in the willingness to depend on augmentation systems for safety of flight is their reliability. Simple mechanical systems incorporating gyroscopes have been about as reliable as the basic airframe, powerplant, or aircraft systems when designed as part of the aircraft.

However, even after many years of development electronic equipment such as the common aircraft radio, navigation equipment, and weather radar present more continual maintenance problems than other aircraft systems. Incipient failures cannot be detected readily. Teardown preventive maintenance inspection is generally frowned upon by electronics people. Even with complete test equipment, difficulties are not easily isolated exactly and correction is often by trial and error. At one time Langley used an autopilot in a research helicopter that performed for several years without problems, and then malfunctions developed that took 2 years to correct. This experience does not seem to be unique. I do not have actual figures available, but informal discussions with military operating squadrons have indicated that in some cases no more than 50 percent of their helicopters could be put into the air with completely functioning stabilization equipment after it has been in the field for a few months.

NASA experience acquired in its VGH program and reported in reference 9, "Operational Experiences of Turbine-Powered Commercial Transport Airplanes" is of interest here. The recorded data of this report correspond to 3/4 of 1 percent of the total turbine fleet time up to the middle of 1962. Unusual occurrences in the form of longitudinal oscillations of differing nature were noted for 22 aircraft of 6 different types operated by 12 airlines. The sources for oscillations induced by the autopilot in these experiences included:

a. Air data computer difficulties with electrical amplifiers, shaping networks, etc.

b. Air data and attitude sensors - lag in tubing from pressure sensors, mismatched accelerometers, malfunction of attitude gyros

c. Electrical power amplification

d. Friction

e. Gain - low damping on high gain

f. Servo clutches - hanging

g. Limited control power available at high speeds

Changes in the nature and occurrence of such problems on some of the airplanes was found to be related to scheduled maintenance.

A contributing factor was also noted as follows: "These newer aircraft are flying faster and higher which, with the attendant reduction in damping, may be expected to make them more sensitive to oscillations induced by the autopilot and control system."

It is felt that a good deal of this airplane experience is applicable to the coming generation of higher speed helicopters, particularly since the helicopter's level of inherent stability and vibration are not yet the equivalent of the transport airplane.

The point to be made is that the reliability and maintainability of sophisticated augmentation systems are not yet up to those of the pilot, the basic control system, and the aircraft structure.

Authority

A basic requirement when applying augmentation to any aircraft is that the aircraft have sufficient control moments available throughout its flight envelop to control any static or dynamic instabilities that might exist. The augmentation cannot do any more than the human pilot can, obviously, if a control reaches its stop.

The primary factor that determines the control authority needed for the augmentation system is the relationship of moments required to control the aircraft to moments available from the control system. Generally higher control moments and more authority will be required where static instability exists than where only dynamic stability must be provided. It has been suggested by Tapscott in reference 7 that 50 percent of the control moment from level-flight trim to the stops remain for recovery throughout the flight envelop in the case of inherent instability. Reference 8 is a little more stringent in that it requires that 50 percent of a "nominal" control moment remain for recovery. The "nominal" control moment is half the total moment available from stop to stop. The latter, in effect, limits control authority of single-channel augmentation to 25 percent when considering the hard-over failure case. An authority of 40 percent would, on the basis of reference 8, leave 20 percent of the "nominal" control moment for recovery. A margin of 20 percent is considered too little for dynamic maneuvers and turbulence, however.

Examination of figure 3 shows that in a maneuver of 1.5g with an unstabilized single-rotor helicopter 25-percent control authority would be exceeded in counteracting the longitudinal instability beyond 100 to 110 knots and 40-percent authority would be exceeded beyond about 130 knots. Actually, if the aircraft had the stability with speed of the rotor shown in figure 5 a total of 40-percent authority would be exceeded beyond 115 to 120 knots. If reasonably high speeds are to be obtained safely with this helicopter, it is obvious that the inherent stability would have to be improved.

The tandem helicopter having very much more powerful longitudinal control can, with the same stability, manage with far less control authority for stabilization in pitch than the single-rotor type. However, there are other considerations in selecting a satisfactory combination of static stability and authority. One consideration is that of safety in case of a hard-over failure of the augmentation about the pitch axis. Figure 9 shows a computed time history of a hard-over nose-up input from a 25-percent authority system of a tandem helicopter whose divergence characteristics at 160 knots were shown in figure 4. Under these conditions the aircraft would reach $2\frac{1}{2}$g and a nose-up attitude of about 20° in 1 second, hardly enough time for a relaxed pilot to cope with, even with his hand on the stick.

If this aircraft had half the positive angle-of-attack stability that it has negative stability and the augmentation system control authority could be cut to 10 percent, the response to the hard-over would be as shown for the stable helicopter in figure 9. At the end of the first second the acceleration would be a modest 0.5g and the attitude change only about 6°, indicating a situation which the pilot could control easily. The acceleration in this case would level off at 1.75g after 3 seconds if no corrective action were taken by the pilot. It is obvious that the inherently stable helicopter could avert disaster in this case.

Another possible occurrence with the twin-turbine powered helicopters is the failure of one engine while in high-power cruise without the pilot recognizing the failure for a short time period. One engine would not be able to sustain rpm with fixed collective pitch. In figure 10 are shown the increments in stick position required to offset the resulting trim change due to a 10-percent loss in rotor rpm at a constant speed for a single-rotor and tandem-rotor configuration as a function of speed. The augmentation system of a single-rotor helicopter would use up a 25-percent control authority at about 150 knots and the tandem would use up a 25-percent control authority at about 200 knots in offsetting this trim change. Of course, once the maximum authority of the augmentation system is exceeded the aircraft behaves according to its own inherent stability characteristics. Figure 11 shows a comparison of the behavior with controls fixed of a stable and unstable helicopter at 160 knots following a small disturbance when the engine failure has used up the authority of the augmentation system. The disturbance was arbitrarily simulated by a pulse of 10 percent of the control power for 0.1 second. If the helicopter is flying at a speed above that where 25-percent authority were exceeded, a disturbance proportional to this speed excess would be generated. For the minimum disturbance illustrated, 2g would be reached in a divergence in a little over 3 seconds and with a corresponding attitude change of about 20° for the unstable case. In this case the time for the pilot to react if he were alert would not be critical, but the behavior of the aircraft would be intolerable when considering the distraction caused by the emergency. In contrast to this behavior the response to the same disturbance in the stable case shown would result in an almost imperceptible departure from initial conditions. Under the stress of the engine failure emergency the inherent stability would assure safe flight.

Redundant Systems

When the authority required for the augmentation system exceeds 25 percent it is considered mandatory to go to redundant systems where the possibility of total system failure is more remote. Objections to use of redundant system are the cost and additional maintenance effort involved. For the time being the possibility of failure or unsatisfactory operation of the complete augmentation system must be considered. The solution to this possibility is, again, to provide adequate inherent stability in the aircraft to fall back upon.

REQUIREMENTS FOR ACCEPTABLE INHERENT STABILITY

To the best of the authors' knowledge no commercial transport airplane has been certified with static instabilities such as I have described for the helicopter within the normal flight envelope of the aircraft. A case of neutral longitudinal stability with respect to speed and a mild nose-down trim change at high Mach number inherent in the configuration has been accepted recently after an automatic corrective device was applied. Stability augmentation in commercial transport airplanes otherwise has been applied almost entirely to achieve dynamic stability.

Although the Military have more detailed and stringent stability and control requirements for aircraft than do the civil authorities, they have often used the option of sacrificing some desirable flying qualities in favor of accomplishing military objectives. Therefore, in the interests of increased payload and desirable cargo-handling capability some military helicopters are now relying on stability augmentation systems to attain satisfactory flying qualities. The civil authorities have seen fit to follow suit in the certification of commercial transport helicopters.

However, from the previous discussions the authors have concluded that sophisticated augmentation systems, particularly electronic types, will have failure rates to reckon with for the near future. The failures that must be considered are hard-overs in the single-channel type, and all channels inactive in the redundant type. In either case the aircraft reverts to its inherent characteristics after the failure.

It seems unreasonable to the authors to suggest blanket requirements for all types of helicopters without considering their missions. It is therefore suggested that for this discussion missions be classified according to the following:

A. Short range ($<$50 miles) and VFR

B. Long range ($>$50 miles) and/or IFR

Requirements for inherent stability characteristics should, therefore, be similar to the following:

Longitudinal - For mission category A, some maneuver and speed instability is acceptable. However, it is suggested that requirements similar to the following be established:

1. A divergence from steady trimmed flight following an 0.25g, 1/2-second pulse disturbance shall not exceed a rate such that an 0.5g increment from trim is exceeded in less than 3 seconds with controls fixed after return to the trim position.

2. The response to a hard-over error signal shall not exceed a 1 g increment in less than 2 seconds with the pilot's controls fixed.

3. During steady, laterally level flight, or in any longitudinal maneuver within the flight envelope of the aircraft including a hard-over input from the augmentation system, the increment in control to offset a static instability or negative damping shall never leave less than 50 percent of the "nominal" control moment* in the recovery direction. (*Nominal control moment is here defined as one-half of the total control moment available between forward and aft stops.) This requirement tends to limit control authority for single-channel augmentation systems to 25 percent or less.

For mission category B, the aircraft shall at least be stable in the maneuvering sense with stick fixed. That is, at constant power setting and speed, measured data shall show that the control position moves aft to trim with increasing steady accelerations and/or angular velocities; or as an alternate, that normal accelerations and/or angular velocity time histories become concave downward in 2 seconds or less following the start of displace-and-hold maneuvers. This requirement shall apply up to a steady acceleration of 1.5g. The requirement that measurements show a stable slope is to insure that the aircraft is stable regardless of control power and scatter of data. Also, for helicopters operating above 120 knots a force per g of at least 15 pounds up to 1.5g shall be required. Furthermore, the force per g at any stage of a quick pull-up shall never be less than that under steady acceleration. With regard to speed stability it shall be required that measurements show a stable slope of control position versus speed at constant power settings in the cruise condition, descent, and final approach to landing. The degree of stability here is not of primary concern. Also, it is not considered necessary to specify a stick-force gradient with speed.

Directional - For mission category A positive directional stability shall be required for the cruise condition, the degree being unimportant. Therefore, measured variation of pedal displacement versus sideslip should indicate positive stability for the cruise condition.

For mission category B, the static directional stability shall be positive as specified for category A in cruise, and of a degree such that slow and rapid roll maneuvers with fixed stick displacement performed from level flight, and from a 30° banked turn in one direction to a 30° bank in the other direction, respectively, pedals fixed, shall not result in a delay in development of yawing velocity in the desired direction of more than 2 seconds nor a stopping or reversal of rolling velocity during the maneuver. These requirements shall apply for the cruise condition, descent, and the final approach to landing.

Lateral - The effective dihedral for category A missions need not be positive. However, for category B missions it shall be demonstrated by measurement to be at least positive. The degree is unimportant.

Dynamic stability - The damping of lateral-directional and longitudinal oscillations need not be positive in all cases for category A missions, but shall be damped to the level of Mil H-8501A (ref. 10) for VFR flight as a minimum; that is, oscillations having a period of less than 5 seconds shall be damped to half-amplitude in not more than 2 cycles, whereas oscillations having a period of greater than 10 seconds shall not achieve double amplitude in less than 10 seconds. For category B missions the damping of oscillations shall be that of MIL-H-8501A for IFR flight as a minimum; that is, oscillations having a period of less than 5 seconds shall damp to half-amplitude in not more than 1 cycle, whereas, oscillations having a period of greater than 20 seconds shall not achieve double amplitude in less than 20 seconds.

Damping in hovering - In order to assure safe landing the angular velocity damping in roll and pitch in hovering must be positive and of the level specified for VFR in MIL-H-8501A for both category A and B missions. In general if the damping is such that the time constant in roll and pitch is less than 2 seconds the control characteristics will be acceptable. A specification for damping about the yaw axis is considered unimportant.

METHODS FOR OBTAINING DESIRED INHERENT STABILITY

CHARACTERISTICS IN DESIGN

The question now arises as to what can be done about achieving the inherent stability characteristics called for by the suggested requirements. It is not desired to expound deeply on this subject. However, design methods for achieving static stability and increased damping aeromechanically are available for helicopters, including the tandem type. The best source for this information is reference 11 (NACA Report 1350). At any rate, it can be said that horizontal tail surfaces are being used successfully, particularly on single-rotor helicopters. The use of mechanical gyro systems to increase damping has also proved advantageous and satisfactory where they have been incorporated into the basic design. The added damping in the longitudinal case increases the apparent angle-of-attack stability, or the so-called maneuver stability. The hingeless rotor promises great improvement in stability and control characteristics because of the large increase in damping and control power it provides. Other improvements in longitudinal stability can be achieved by increased rotor rpm, by moving the center of gravity forward in combination with offset hinges in the single-rotor case, and by changing the relative geometry of the two rotors in addition to moving the center of gravity forward in the tandem case.

SUMMARY AND CONCLUSIONS

Some of the static instabilities in forward flight which have been encountered in helicopters and are still present to some degree in current aircraft without stability augmentation are dangerous and very demanding of the pilot during long flights or during instrument flight operations.

Sophisticated augmentation systems, particularly electronic, are not considered to have the degree of reliability necessary to be entrusted with safety of flight. High authority, redundant systems may be desirable and necessary for specific portions of the design mission such as the low instrument approach, but if inoperative they should not prevent a safe recovery, the safe use of the aircraft on an alternate mission, or safe return to an alternate base.

On the other hand, stability and control augmentation may be necessary to obtain, not only satisfactory, but desirable handling qualities to aid the pilot in his mission. If the aircraft has acceptable inherent stability characteristics, relatively cheap and simple, limited-authority, single-channel systems can be used to satisfactorily augment the aircraft characteristics. Failure of the augmentation in this case does not destroy the mission capability entirely, nor the safe return to a landing. Also, since adequate inherent stability keeps the required authority of the augmentation system low, protection of the aircraft against hard-over failures is no problem.

The suggested requirements for satisfactory inherent stability are, in general, variations of requirements from AGARD Report 408 (ref. 8) and MIL Spec H-8501A (ref. 10).

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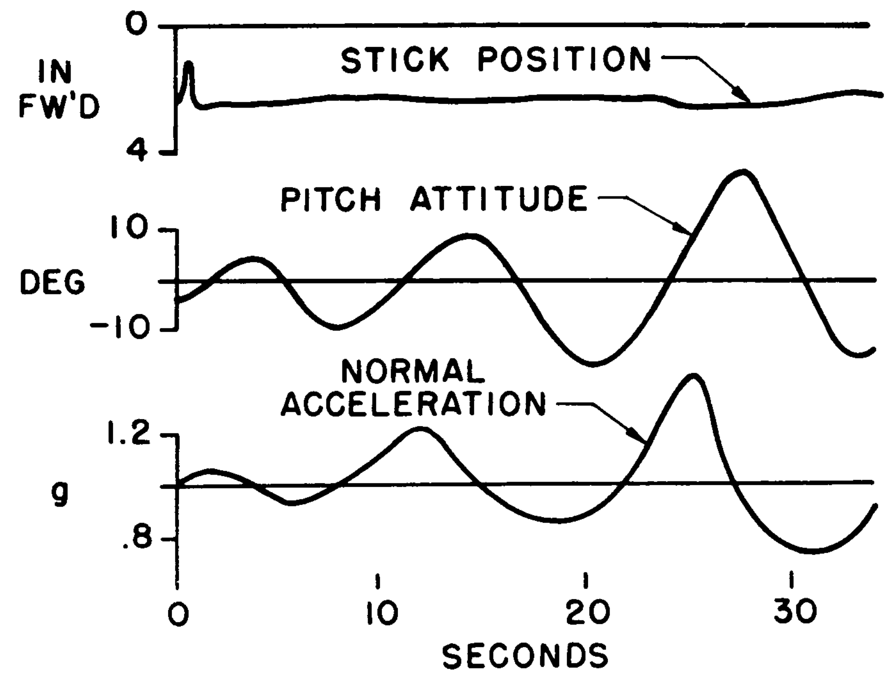

Figure 1.- Longitudinal oscillation at 40-mph, single-rotor unstabilized helicopter.

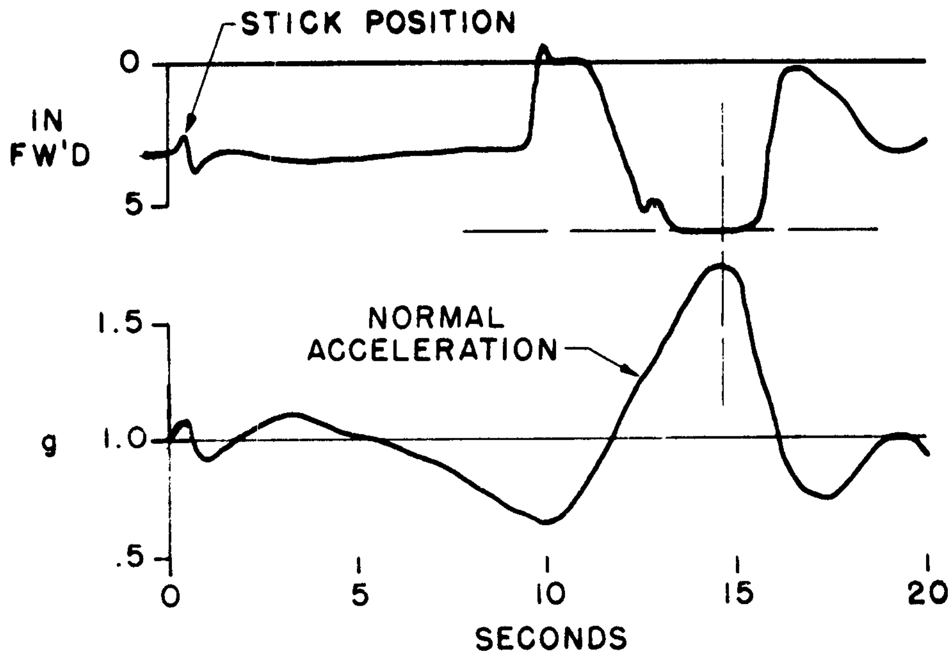

Figure 2.- Longitudinal divergence characteristics at 65-mph, single-rotor unstabilized helicopter.

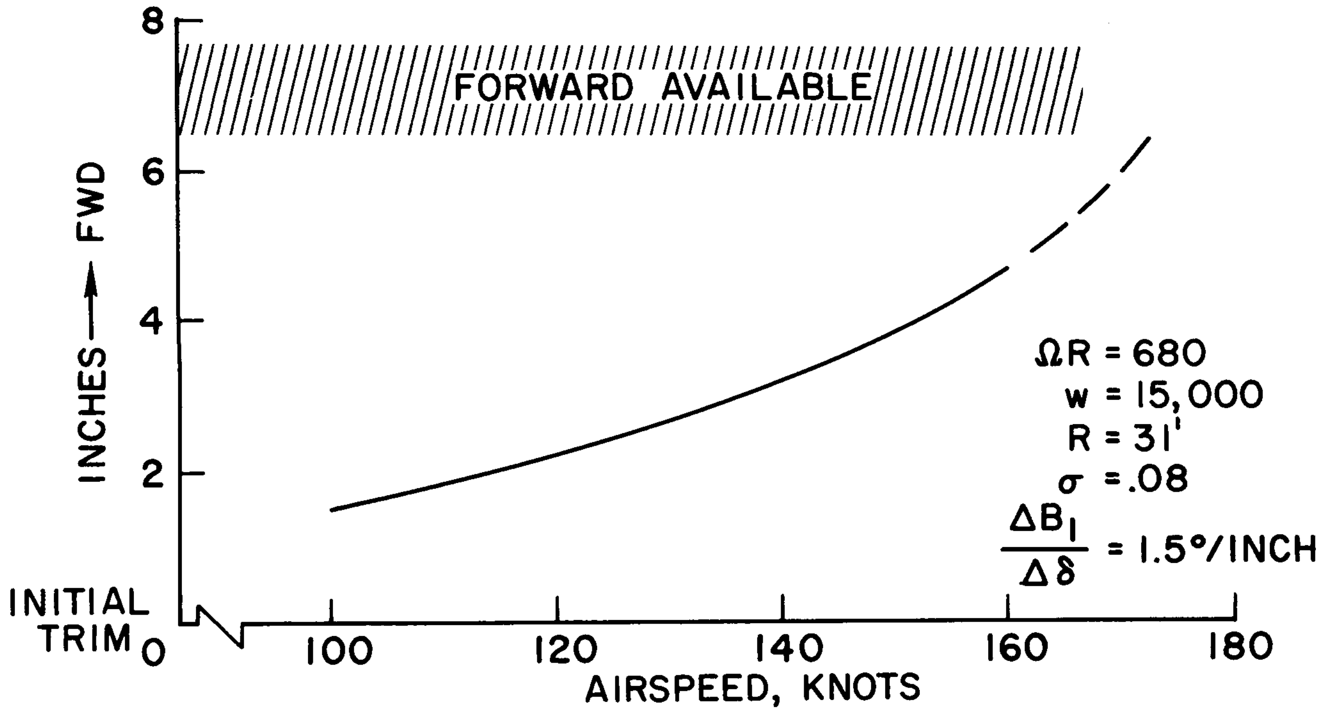

Figure 3.- Control increment required to trim a 1.5g maneuver, isolated rotor.

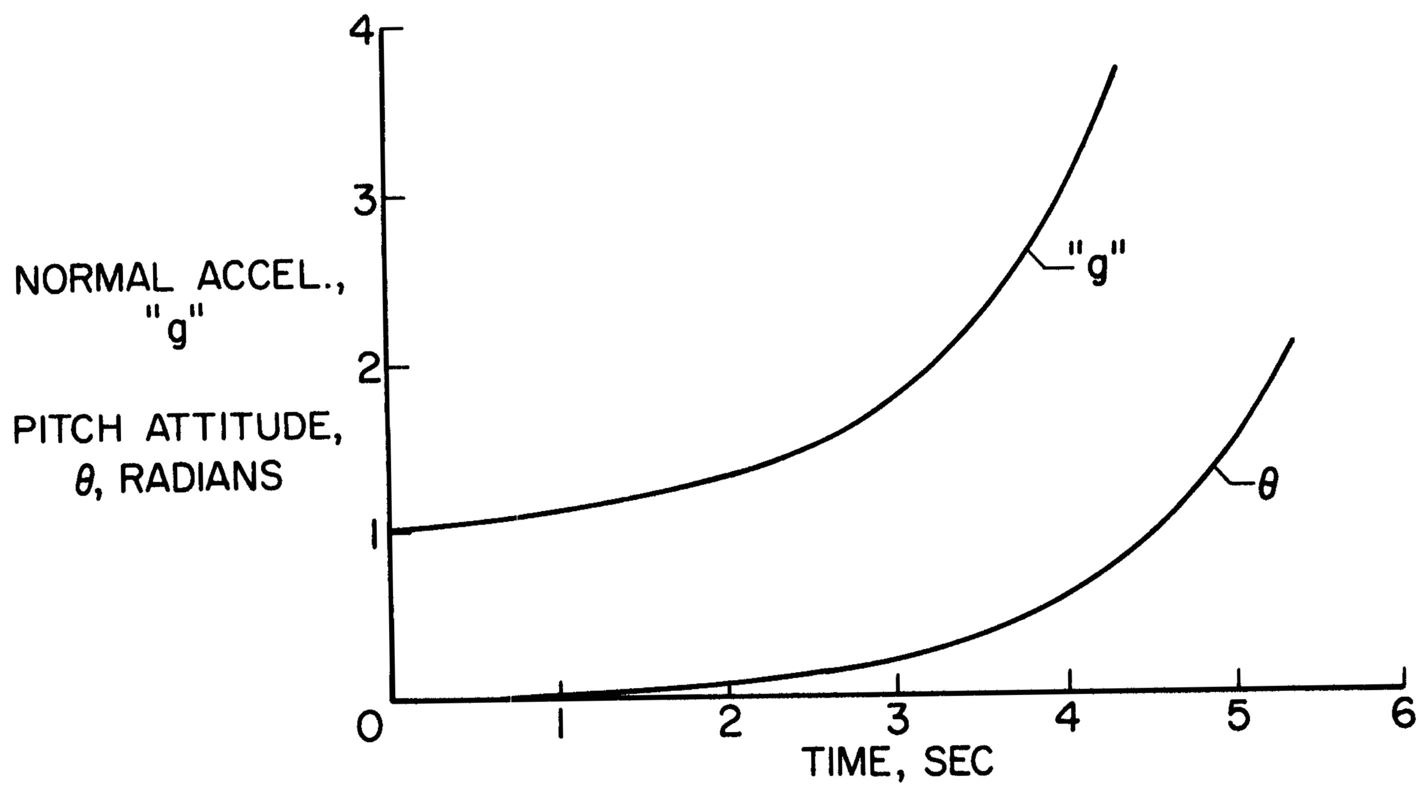

Figure 4.- Divergence of unstable tandem-rotor helicopter following 10%, 0.1-sec control pulse, 160 knots.

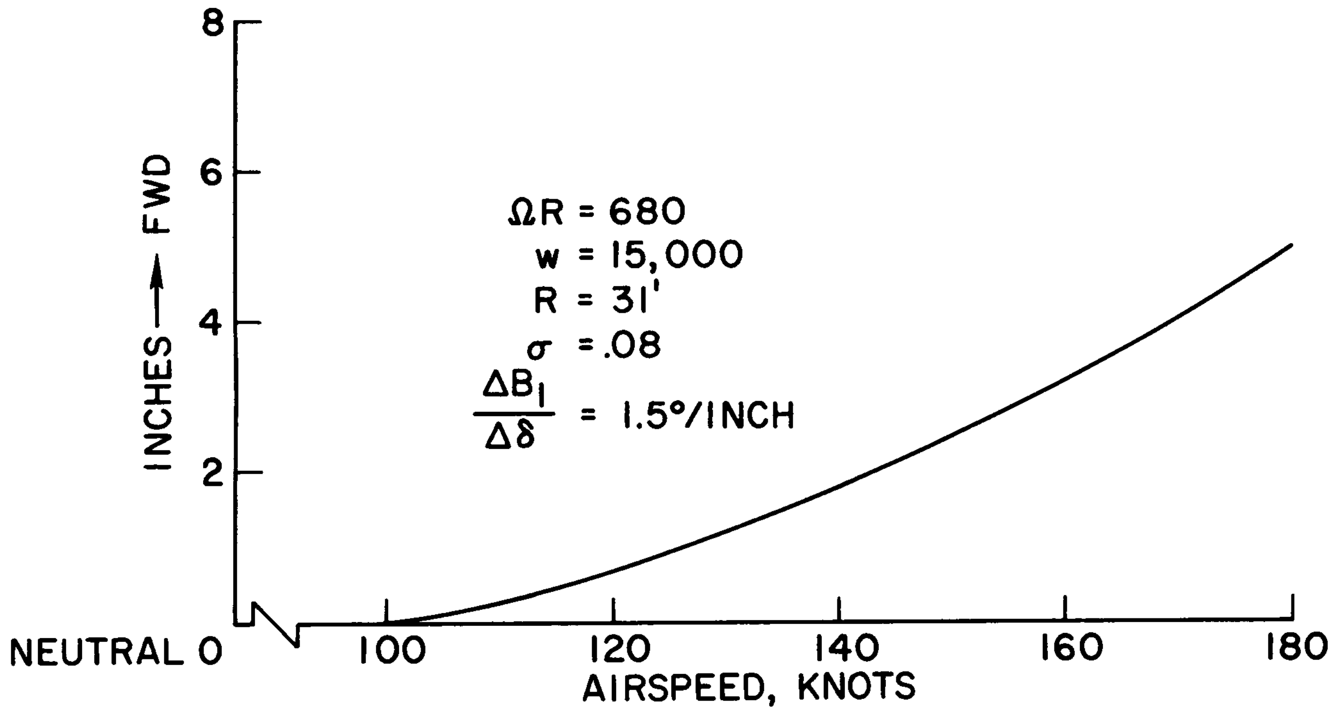

Figure 5.- Control position increment to trim with speed, isolated rotor, control assumed neutral at 100 knots.

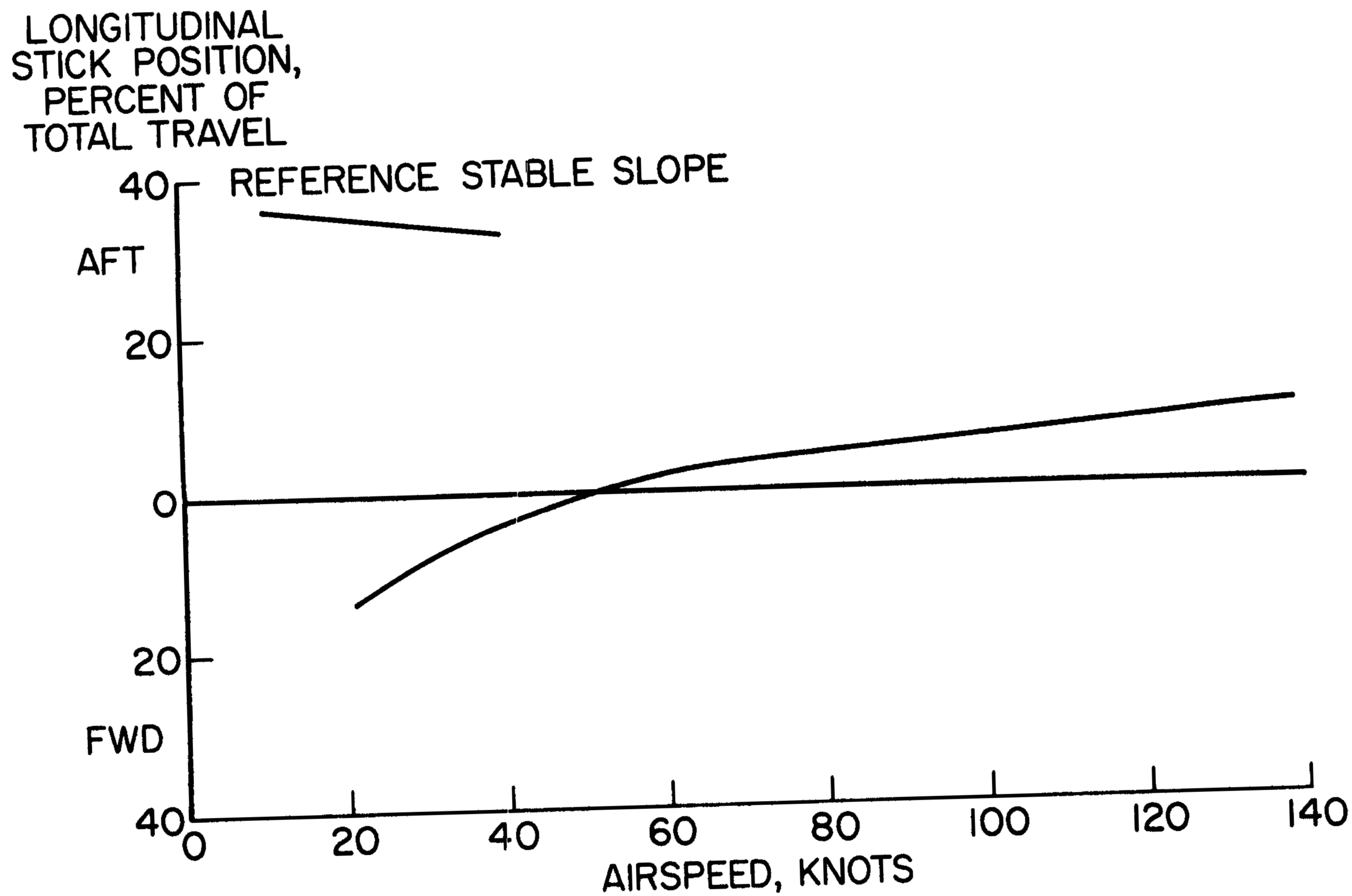

Figure 6.- Longitudinal stick position for trim with speed, tandem-rotor helicopter, power for level flight at 80 knots.

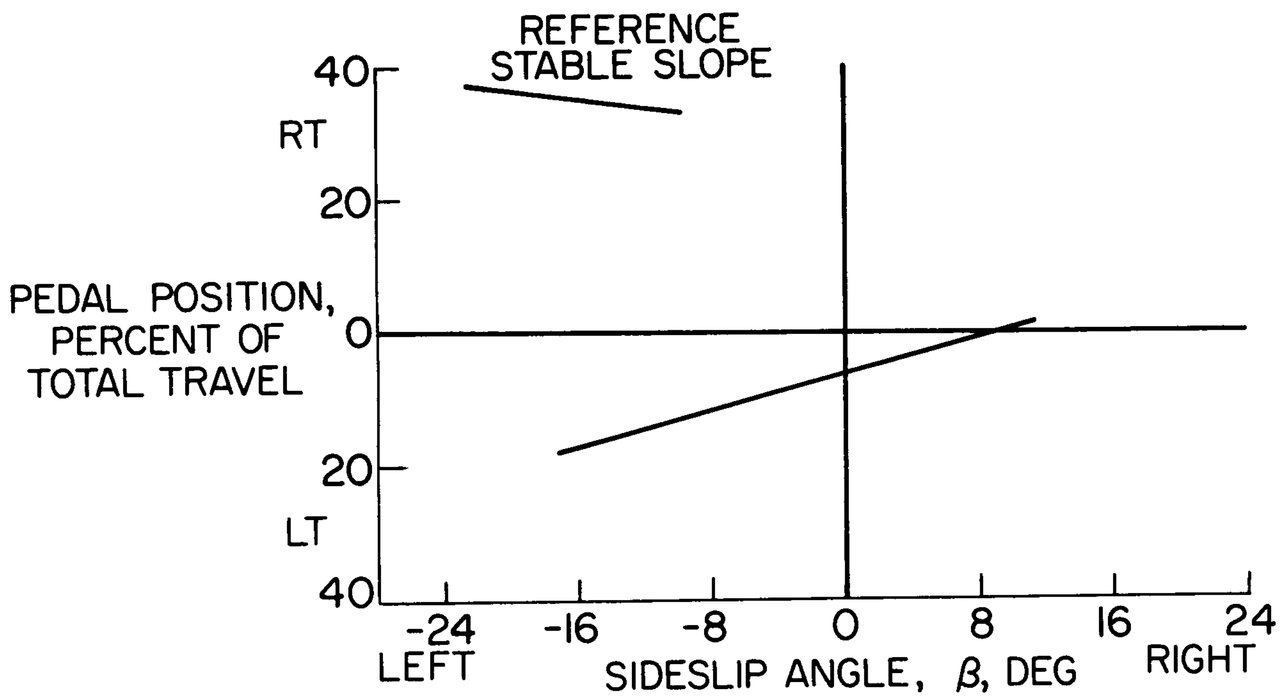

Figure 7.- Pedal position with sideslip angle for tandem-rotor helicopter, power for level flight at 80 knots.

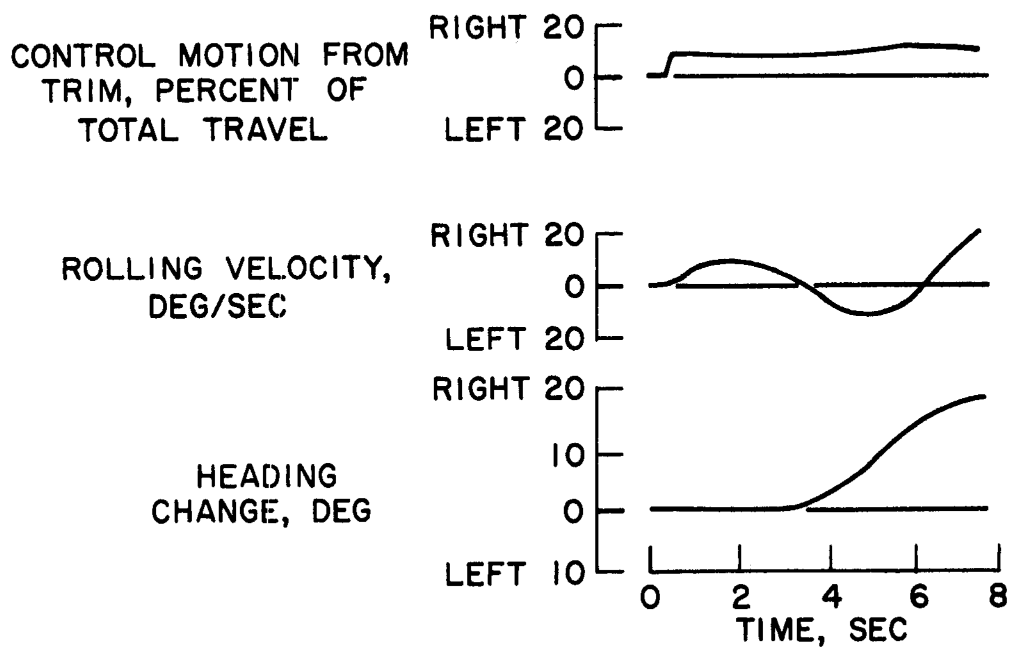

Figure 8.- Lateral control of a tandem-rotor helicopter, pedals fired at 70 knots.

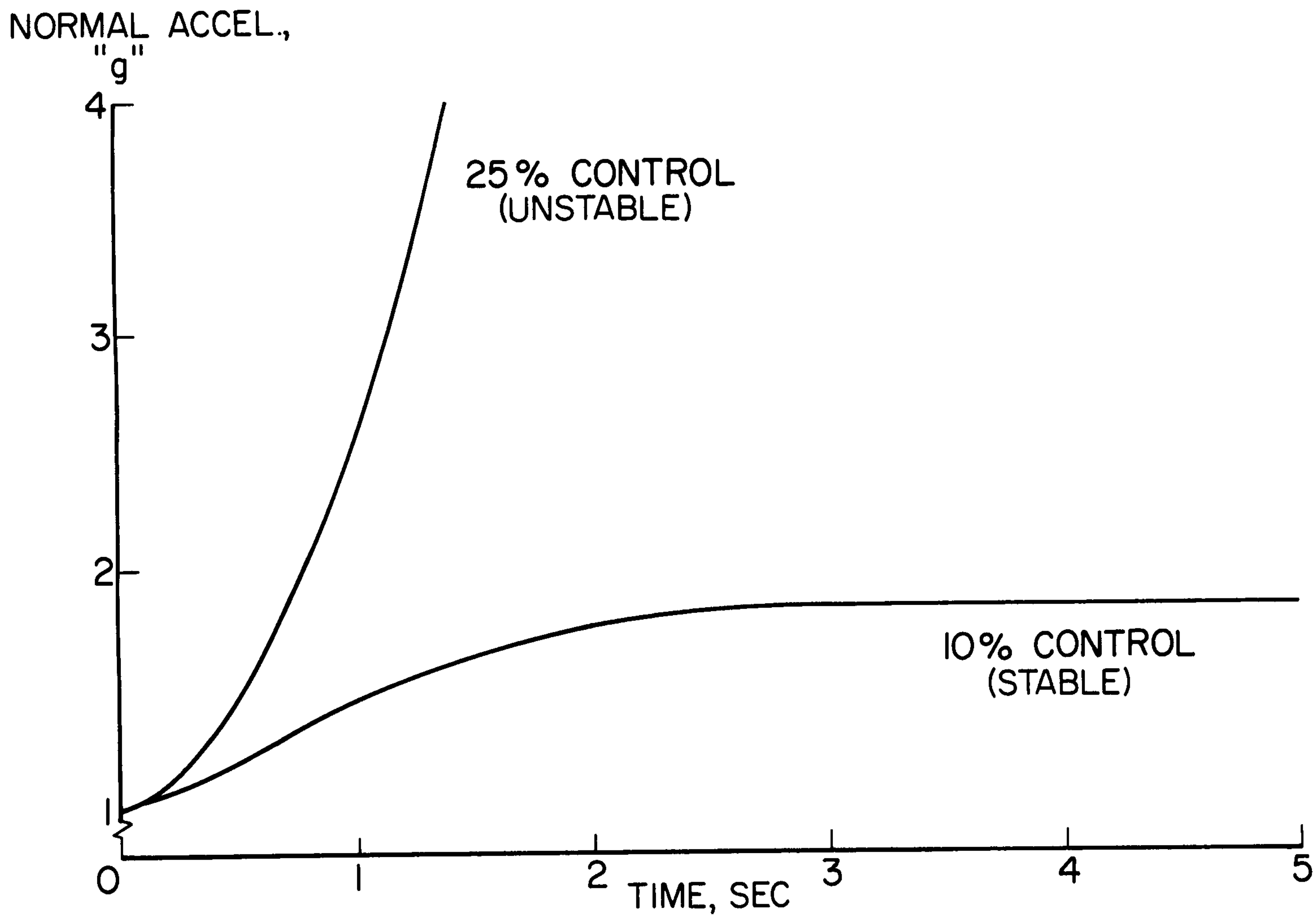

Figure 9.- Response due to hard-over control inputs for stable and unstable tandem-rotor helicopters, 160 knots.

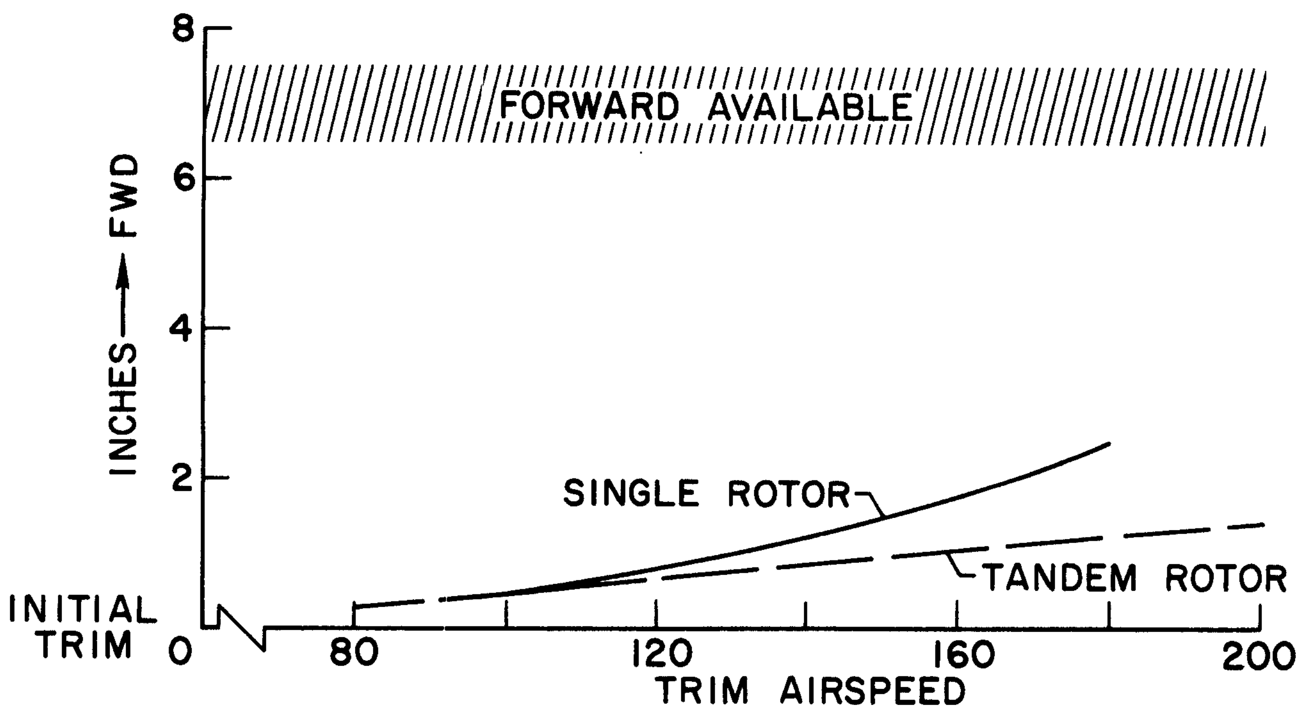

Figure 10.- Control increment required to trim moments caused by 10% loss in rotor rpm.

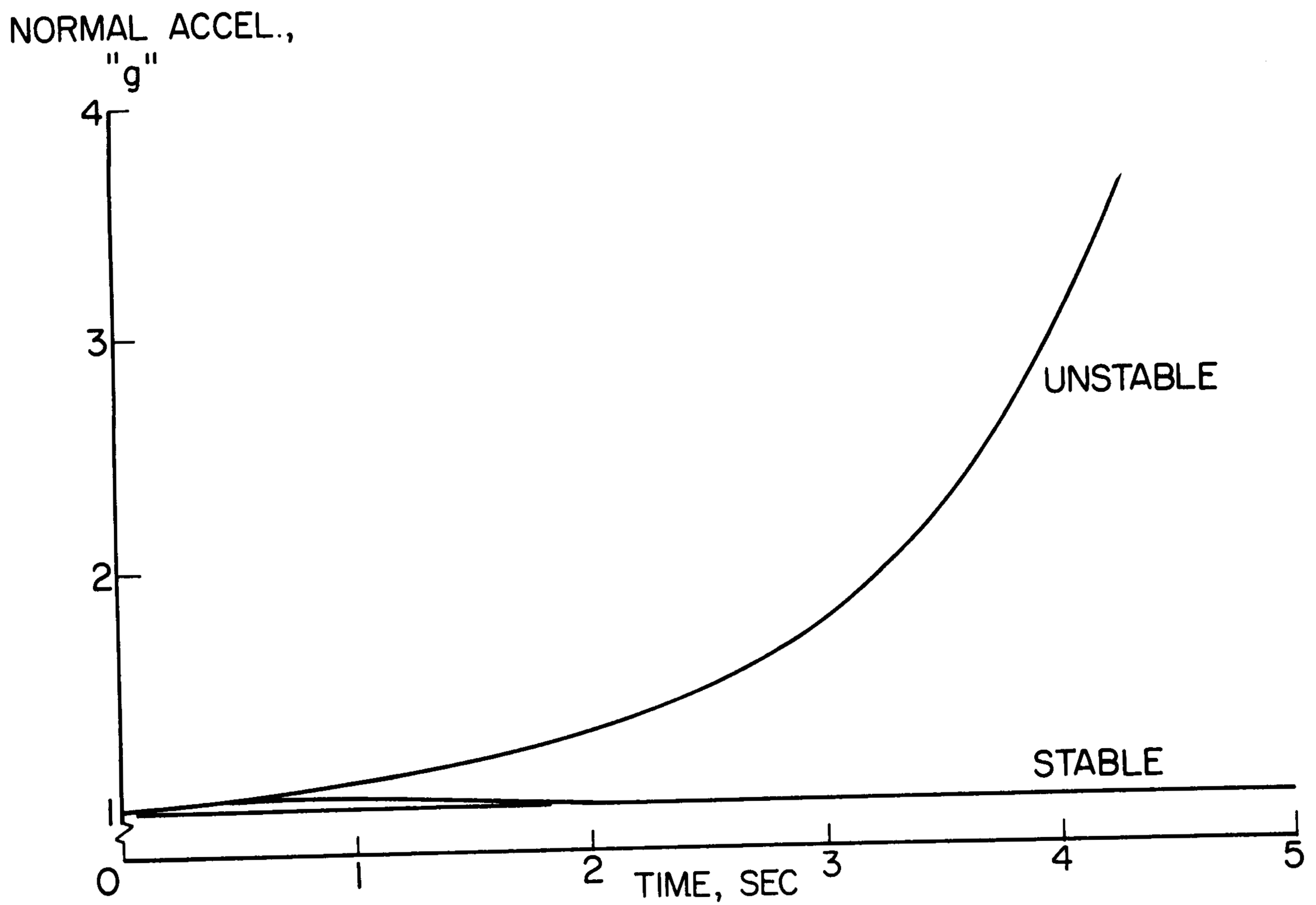

Figure 11.- Response of tandem-rotor helicopters to a 10% control, 0.1-sec pulse, 160 knots following 10% loss in rpm.

NASA-Langley, 1966